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Electro dynamic fragmentation of printed wiring boards as a preparation tool for their recycling

Rémi Martino [a], Cédric Iseli [b], Stoyan Gaydardzhiev [a,*], Martin Streicher-Porte [b], Alexander Weh [c]

[a] University of Liege, GeMMe-Mineral Processing and Recycling, Sart Tilman, 4000 Liege, Belgium
[b] University of Applied Sciences and Arts Northwestern Switzerland - FHNW, Klosterzelgstrasse 2, CH-5210 Windisch, Switzerland
[c] Selfrag AG, Biberenzelgli 18, CH-3210 Kerzers, Switzerland

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ABSTRACT

The use of Electro Dynamic Fragmentation (EDF) enables selective fragmentation of materials through generating electrical discharges as a means of fracturing. Liberated materials can be thus processed downstream in a more efficient way especially when value-added End-of-Life (EoL) electronic equipment is recycled. The aim of this study was to assess the benefits of the EDF technology towards processing of EoL printed wiring boards (PWBs) in view their recyclability. Printed wiring boards were comminuted using EDF at three different settings and with a hammer mill for comparative experiment. The products coming out were characterized by optical microscopy, SEM and liberation oriented leaching. Subsamples from the various EDF stages were inspected to investigate the progress of cracks and degree of copper layers exposure. The different energy levels used during the EDF processing have resulted in different degrees of PWBs damages, starting from components removal to entire structure perturbation and size reduction. EDF has resulted in generation of a lesser amount of fines, however the optimal approach in view energy efficient post-processing of the studied PWBs was the combination between single-stage EDF for components removal only with subsequent shredding of the depopulated boards.

1. Introduction

Recent statistics indicate that within the EU, only for the year of 2012, 9.1 million tonnes of electric and electronic equipment (EEE) were put on the market, while 3.5 million tonnes of waste EEE (WEEE) were collected and processed. Similar figures are reported for 2013 with 3.6 million tonnes of WEEE being treated. Out of this amount, about 2.4 million tonnes were recycled with objective of material valorisation and 0.2 million tonnes were used for energy production (Eurostat, 2016). WEEE usually contain non negligible amounts of different base and precious metals (up to 61%), and polymers (up to 21%) which renders them attractive as secondary resources compared to the primary mineral based ones (Tuncuk et al., 2012).

Various recycling technologies exist to process End-of-Life (EoL) printed wiring boards (PWBs), like for example direct treatment (i.e. without size reduction and removal of attached components) which targets both copper and precious metals recovery. In this case, the initial pyrometallurgical step is generally followed by subsequent hydrometallurgical and electrometallurgical operations. During pyrometallurgical treatment, the polymers, which form integral part of the PWBs, are used both as reduction agent as well as energy source due to their intrinsic calorific value. Nevertheless, pyrometallurgical operations require extensive off-gas cleaning systems to prevent emission of hazardous substances to the environment. The smelting step results in a precious metals rich copper mate phase and a lead slag. Following this step, hydro- and electrometallurgy are employed to recover copper through electrowinning and precious metals are subsequently refined (Schluep et al., 2009).

Hagelüken (2006a) mentions that the interaction between smelting installations and dedicated pre-processing and sorting plants should be considered with care as they both could benefit from mutual optimisation. The same study suggests that there is a room for improvement in this direction and points out that the recovery rate of a given element from an input stream is inversely proportional to its concentration in the output fraction. This highlights the potential for ever more selective fragmentation techniques. Parallel to pyrometallurgical processes description, many papers have referred to development of hydrometallurgical techniques for PWBs recycling. Notwithstanding, Schluep et al. (2009) mention that in contrast to pyrometallurgy which has proven track records, there is no sufficient data available in the public domain to

* Corresponding author.
E-mail address: S.Gaydardzhiev@ulg.ac.be (S. Gaydardzhiev).

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conduct an independent review of a hydrometallurgical process for recycling of PWBs in order to prove its efficiency, sustainability and environmental performance. Nevertheless, toxic fumes generation and high investment and operating cost still remain as drawbacks for the pyrometallurgical option. Schluep et al. (2009) further add that it would be possible to treat complex wastes such as copper and precious metals bearing PWBs in classical smelters in China or elsewhere, but the installation of an off-gas treating systems as well as the highly sophisticated operation of these smelters would be expensive and more difficult to step up. It is shown that although traditional process routes possess their proven niches, trying new techniques and possibilities as a way to further process improvement is to be equally encouraged (Reuter et al., 2013).

In a recent scoping study primitive methods for PWBs recycling are mentioned to be used in some workshops in China (Guo et al., 2009). These techniques include open-air burning and acid washing of PWBs and provoke organic compounds release into environment. In particular, polybrominated diphenyl ethers (PBDEs) which are commonly referred to as brominated flame retardants, are emitted. In contrast, within the EU, WEEE streams and their processing are regulated through legislative acts such as the WEEE and RoHS directives (Tuncuk et al., 2012). The WEEE directive for instance, discusses reuse and recycling of WEEE with the objectives of reducing the ultimate amount of waste disposed and improving the environmental aspects around WEEE processing (Eurostat, 2016).

Whatever the processing method for WEEE, apart from environmental issues, the economic incentive is a factor of important consideration. The concentration of base and precious metals being the main materials targeted has to be taken into account accordingly in view of process selection and dimensioning. Hagelüken (2006a) mentions three grade categories for e-wastes based on their gold content. Low grade: with concentration below 100 ppm (e.g. TV-boards); medium grade comprising between 100 and 400 ppm (PC-boards, laptop-computers, some mobile phones) and high grade - above 400 ppm (e.g. some mobile phones, ICs, MLCCs). Whilst various studies dealing with the average metal grades in PWBs exist, Tuncuk et al. (2012) citing Hagelüken (2006b) report that for PC derived PWBs one can expect the following concentrations: Cu 20%, Au 250 ppm, Ag 1000 ppm and Pd 110 ppm. It is logical to assume that these metals are somehow repartitioned between the boards and the components on them. In a way to ease PWBs processing it might prove therefore feasible to separate components and depopulated boards into two individual streams, with each of them to be treated in a dedicated manner. In that context, Wang et al. (2016) have described various methods of removing the components from waste PWBs however the use of EDF for this purpose has been virtually not reported. From other hand, only few studies have appeared so far dealing with high-voltage comminution of entire WEEE (Duan et al., 2015; Zhao et al., 2015).

The EDF technology has attracted several studies during the recent years, among them (Wang et al., 2011), (Shi et al., 2013) and (Razavian et al., 2014) have investigated its use as a pre-weakening tool for mineral ores. This interest was provoked mainly due to the inherent fragmentation principle which differs radically from the breakage mechanism of traditional crushers. EDF does not blindly fragment the material, but induces fractures according to the intrinsic properties of the material, in particular the contrast between dielectric constant of the different phases (SELFRAG communication, 2016). In further studies, Wang et al. (2012) have compared the mineral liberation achieved by EDF and traditional comminution at identical specific energy inputs. Van der Wielen (2013) has extensively compared the EDF impacts on various rock types. These experimental works have been based on the use of the SELFRAG Lab system, which is a batch one. Recent research however has been conducted towards setting up continuous equipment, for instance fragmentation of mineral ore has been studied in pilot scale continuous EDF equipment (Zuo et al., 2015).

Whilst most of the EDF application research done by far was focused on mineral ores, the EDF technology has a chance to penetrate into circular economy concept notably within high value materials recycling like for example carbon fibres (Roux et al., 2014). It is worth to mention that EDF-based bottom ash treatment plants and silicium rod crushing plants are currently being installed by the SELFRAG AG.

With the above mentioned on the background, the current work places a particular emphasis upon the pre-treatment of PWBs with an EDF technology using a SELFRAG Lab system. A secondary objective was to try to compare the SELFRAG system with a traditional shredding equipment in terms of resulting structure of the material and whenever possible energy consumption. The latter however appears quite tricky in practice, since energy in shredding depends on many factors such as output size, dimension and throughput of the shredder used (in our case hammer mill), filling degree of the chamber and others. From other hand, during EDF, output results are directly dependent on the amount of energy dissipated through the sample controlled via operating parameters such as voltage, frequency, and number of applied pulses. Moreover, the EDF equipment used in this study is a Selfrag Lab batch mode unit and as such is less energy efficient than a continuous machine. The same however is valid for the comparative unit used, being a semi-batch mode laboratory scale hammer mill. Another aim of the work was to develop and verify a methodology for tracing the liberation of the copper foils from PWBs during EDF processing and to compare its liberation degree with the one of a traditional shredder. Given the specific resulting impacts from the EDF, it is tangible to anticipate effects such as PWB depopulation and delamination.

2. Materials and methods

Representative PWB samples have been provided by the project partner Immark AG, Switzerland. Initial exploratory tests have been conducted using randomly picked PWBs originating from obsolete computers, with more detailed experimental work being performed on identical motherboards delivered by Immark AG.

A combination hammer-knife mill manufactured by Laarmann (the Netherlands) has been used as comparative grinding device. It is a custom-developed mill based on a CM4000 platform having the possibility to switch between knifes and hammers fixed onto rotating head. A 10 mm screen is placed inside the grinding chamber so that ground material granulometry is always below 10 mm. Depending on the mode (knifes or hammers), the maximum power output varies between 5.5 and 8.8 kW. Rotation speed is adjustable as well, and in this study has been set to 1025 rpm. The gap between the hammers and the fixed plates has been set to 3.5 mm.

A major challenge when designing process flow sheet for PWBs is the sample representativeness. Samples which appear similar may still be very different one from another in terms of chemical composition. Therefore, one needs to be careful with results interpretation in terms of material balancing and rather focus on behavioural trends, especially when performing laboratory scale research. This is due to the extreme heterogeneity of e-waste streams, best represented by the PWBs entering recycling plants. In this study, identical entire motherboards have been water-jet cut always under same procedure to fragments of 4×4 cm and divided into three groups. In a next step, they have been depopulated either by SELFRAG lab system (i.e. at Stage 1 as explained fur-

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